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Research Paper

Viticultural irrigation demands under climate change scenarios in Portugal

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ABSTRACT

Climate change projections for Southern Europe reveal warming and drying trends for the upcoming decades, bringing important challenges to Portuguese viticulture in particular. The present study analyses irrigation as an adaptation measure to ensure the future sustainability of viticultural yields in Portugal. The STICS crop model was used to simulate baseline (1981–2005) and future (2041–2070) grapevine yields in Portugal. Future yield decreases (yields are 60% with respect to baseline) over some of the innermost and most renowned winemaking regions of the country are found, following the decrease of precipitation in the growing season. As an adaptation measure, grapevine irrigation was tested for future climates. STICS irrigation replicates a highly efficient water use strategy, only applied when a certain water stress level is reached. The results indicate higher yields with this irrigation strategy, thus largely alleviating the projected yield decreases. Nonetheless, in some warmer and dryer regions, such as inner Alentejo and Douro/Porto, yield levels are still projected to decrease with irrigation (70–80% of baseline yields), though to a lesser extent when compared to non-irrigated simulations. This decrease is attributed to the synergistic effect of severe heat and water stresses in the future. Although these simulations aim at achieving the same yields and alcohol level in future scenarios as in baseline, applying irrigation may modify the wine typicity of each region and threaten the currently scarce water resources. Outlining appropriate, timely and cost-effective adaptation measures is critical for the sustainability of both the environment and the national Portuguese winemaking sector.

1. Introduction

Grapevine growth and development is largely controlled by atmospheric conditions (Jones and Goodrich, 2008; Jones et al., 2005; Tonietto and Carbonneau, 2004; van Leeuwen et al., 2004). In fact, weather factors such as temperatures, solar radiation and water availability strongly influence vine growth and development, which ultimately impact yield and wine quality (Makra et al., 2009; van Leeuwen et al., 2008). Although grapevines show a strong adaptation to different environmental conditions, many of the renowned winemaking regions worldwide are located in areas with Mediterranean-type climates, characterized by stressful conditions for plant growth (Fraga et al., 2016a; Toth and Vegvari, 2016; van Leeuwen and Darriet, 2016). In Portugal (Fig. 1), grapevines are often exposed to severe heat and water stresses, in the most internal regions during summer. In the Douro/Porto wineregion (Fig. 1), world renowned for its Port Wine, total precipitation in the summer months (June-July-August) is usually around 100 mm (Fraga et al., 2015).

Water is essential for grapevine vegetative and reproductive growth, being a major forcing factor of crop yields (Hardie and Martin, 2000; Iglesias and Garrote, 2015). Water availability, while more critical at certain development stages, will define in most the case, the crop suitability (feasibility) in a specific area (Caubel et al., 2015). Severe water stress may result in a wide range of negative impacts, such as low flower- and berry-set, low leaf area, limited photosynthesis, flower abortion and cluster abscission (During, 1986; Hardie and Considine, 1976). Conversely, excessive humidity overstimulates growth, leading to denser canopies and higher risk of specific pests and diseases. Additionally, for the production of a high quality wine, a certain level of water stress at certain development stages may be required (Jones and Davis, 2000; Nemani et al., 2001; Ramos et al., 2008; Reynolds and Naylor, 1994; Storchi et al., 2005; Tonietto, 1999).

For the Portuguese viticulture, which is currently the European 5th largest wine producer, with a total of 6.7 Mhl (IVV, 2015; OIV,

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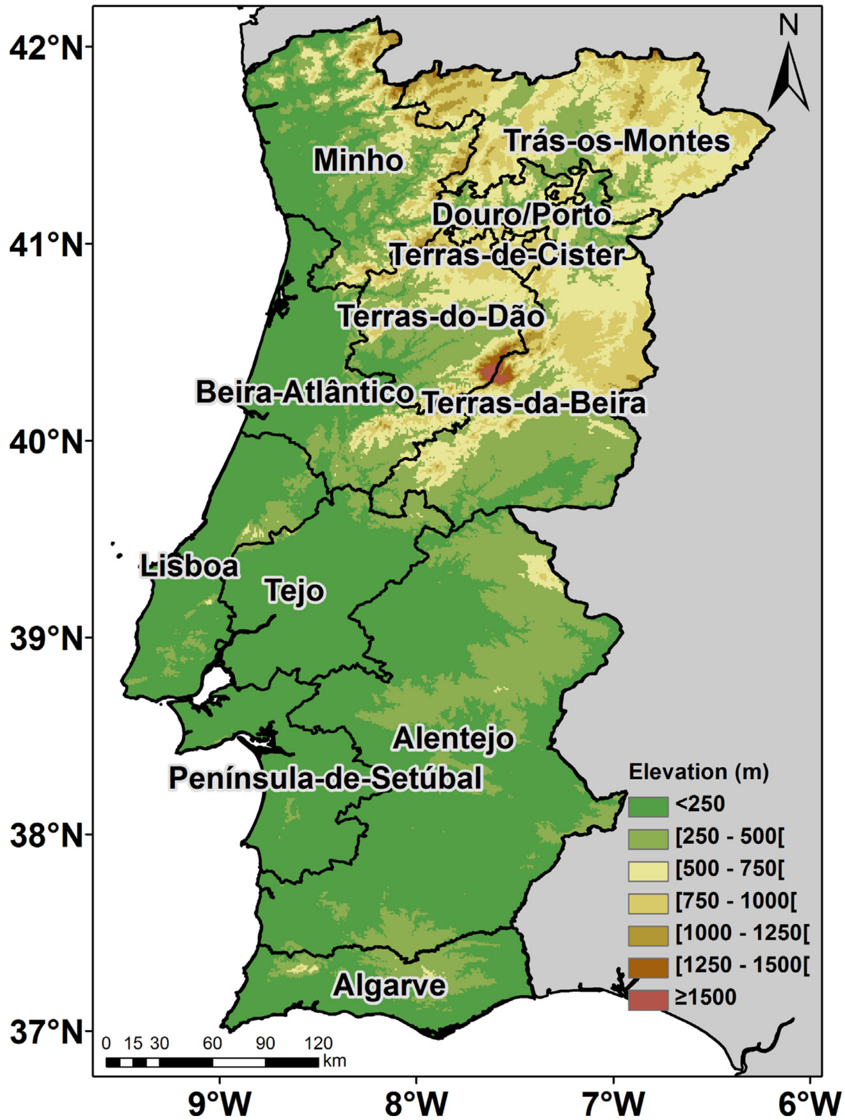

Fig. 1. Grapevine growing regions in mainland Portugal as defined by the *Instituto do Vinho e da Vinha (IVV)*.

2015), precipitation is, for most regions, traditionally considered the only source of available water for plant growth. In almost all of the 12 Portuguese mainland viticultural regions (Fig. 1), water stress levels can be severe, especially in the warm and dry summers. Irrigation application is often not advised, or even not allowed, as it can alter grape yield and quality attributes. In many European countries, this practice has indeed been historically forbidden by strict wine regulations, specifically established for each winemaking region. This is also the case of the Portuguese Douro Demarcated Region, where irrigation has been outlawed, except in very specific cases (e.g. experimental plots, vineyards endangered due to excessive water stress). Despite this limitation, viticultural irrigation in Portugal has been increasing, though still limited to the dryer inner-southern areas of the country, such as in Alentejo (Costa et al., 2016; Permanhani et al., 2016).

Climate change may challenge these traditional concepts (Fraga and Santos, 2017; Fraga et al., 2016b; Jones, 2005; Kenny and Harrison, 1992; Neethling et al., 2016; Nesbitt et al., 2016; Toth and Vegvari, 2016). In the future, the projected lower precipitations in Southern Europe, combined with higher temperatures and more frequent and longer extreme climate events, such as heat waves and extreme droughts (IPCC, 2013; Santos et al., 2017), may negatively affect final yields and quality attributes (Jones and Alves, 2012). A recent study clearly points to a decrease in yields over some areas of Portugal under climate change scenarios if no adaptation measures are adopted (Fraga et al., 2016a). These findings are encouraging the research and development of climate change adaptation measures, namely the implementation of irrigation systems (Costa et al., 2016; Permanhani et al., 2016). As a result, throughout Southern Europe, many winemaking countries have been loosening their regulations regarding irrigation (Permanhani et al., 2016). Still, the assessment of the potential positive effects of viticultural irrigation under climate change scenarios in Portugal was not previously performed, being of utmost importance for growers.

Under the increasingly dryer Portuguese climates, water is considered a threatened resource. Water scarcity is increasing, not only due to climate change, but also due to population growth, industrial use and intensive agriculture water demands, amongst other factors. Hence, applying irrigation to this historically rain-fed crop brings additional economic, environmental and social costs. As adaptation to water scarcity is required under future climates (Costa et al., 2016), smart (e.g. deficit) irrigation strategies should be implemented (Permanhani et al., 2016; Romero and Martinez-Cutillas, 2012; Santos et al., 2003), both to reduce non-beneficial water consumption (Pereira et al., 2012; Perry, 2011) and to optimize grape composition (Junquera et al., 2012), providing a

balanced solution between environmental costs and plant water requirements (Garcia et al., 2012).

Many recent studies focus on the adaptation of grapevine under future warmer and dryer conditions by testing irrigation under controlled conditions and/or in experimental vineyards (Bellvert et al., 2014; Chaves et al., 2007; Kizildeniz et al., 2015; Oliveira et al., 2011). Nonetheless, a regional scale approach is still lacking, which can provide an answer on how much irrigation water is required to mitigate the detrimental impacts of climate change. A possible solution to this problem is through the use of crop models. Crop models dynamically simulate crop responses to management practices (e.g. irrigation), soil properties (e.g. texture, depth), as well as crop physiological responses to atmospheric conditions (e.g. air temperature, precipitation, CO_2). Hence, by coupling crop models with high resolution climatic simulations, such as the regional climate models from the EURO-CORDEX project (Jacob et al., 2014), a regional characterization of water requirements for grapevines can be accomplished.

The present study aims at characterizing present and future grapevine water requirements and its influences on yields. Therefore, the present study objectives are four-fold: 1) to couple a dynamic crop model with high resolution climatic simulations for current and future climate change scenarios, specifically adapted to the Portuguese viticulture; 2) to assess grapevine yield differences under future climates at a regional scale for each winemaking region; 3) to simulate suitable irrigation strategies to mitigate the impacts of climate change on yield; and 4) to analyze the impacts of the introduction of viticultural irrigation in the future.

2. Material and methods

2.1. The STICS crop-soil model

Grapevine modelling was performed using the STICS (*Simulateur mulTIdisciplinaire pour les Cultures Standard*) crop model (Brisson et al., 2008), developed by the French National Institute for Agronomic Research (INRA). This is one of the few crop models that can be applied to perennial crops, such as grapevines. This model has been tested and validated for grapevines under different management/soil water conditions and irrigation regimes (Coucheney et al., 2015; Fraga et al., 2015; Valdes-Gomez et al., 2009). Furthermore, this model has previously been used in assessing the impacts of climate change on European viticulture (Fraga et al., 2016a). For Portugal, using data from experimental vineyards, this model has previously shown a high agreement between observed and simulated yields, phenology and water stress levels (Fraga et al., 2015). Given the model high skill in simulating grapevine yields and water relations (Fraga et al., 2015; García de Cortazar-Atauri, 2006; Valdes-Gomez et al., 2009), it was used herein to develop different irrigation strategies for climate change adaptation at a regional level.

2.2. Datasets

Several datasets for daily weather variables, soil characteristics, topographic features, management practices and plant data were used as STICS inputs. Daily weather data required for model simulation were: minimum and maximum 2-m air temperature (°C), solar radiation (MJ m^{-2}), precipitation (mm), wind speed (m s^{-1}), water vapour pressure (hPa) and near-surface atmospheric CO_2 concentration (ppmv). These variables were retrieved for the baseline period (1981–2005) from the evaluation run of the Regional Climate Model (RCM) SMHI-RCA4 (Samuelsson et al., 2011), forced by the ERA-interim reanalysis (Dee et al., 2011). It is an observation-based dataset, thus representing the actual atmospheric conditions over the baseline. Data was extracted over the Portuguese mainland at a spatial resolution of 0.125° latitude × longitude, approximately corresponding to 1350 gridboxes.

Regarding the climate change projections, SMHI-RCA4 RCM was driven by two different Global Climate Models (GCM): MPI-M-MPI-ESM-LR (Giorgetta et al., 2013) and CNRM-CM5 (Voldoire et al., 2013) under the Representative Concentration Pathway – RCP8.5 (van Vuuren et al., 2011), and for 2041–2070. Under this future scenario, CO_2 emissions are projected to rise until the end of the 21st century, resulting in an intensification of heat and water stresses over Portugal. Although RCP4.5 was also considered, a previous study shows that this scenarios projects similar impacts on viticultural yields in Portugal (Fraga et al., 2016a). The selected GCMs have previously showed a high skill in simulating current atmospheric dynamical mechanisms over the North Atlantic and Western Europe (Santos et al., 2016), and may therefore be considered suitable for simulating future climates in Portugal. Model data were first submitted to bias corrections using the evaluation run as a reference (Dee et al., 2011).

STICS was initialized, for each gridbox (~1350) of each climate model, for each year in the baseline (25 years; 1981–2005) and future period (30 years; 2041–2070), corresponding to approximately 150,000 simulations. As the two climate models provided very similar outcomes (not shown), only the 2-model ensemble mean will be shown henceforth. For each run, the dominant (most frequent) soil characteristics and topographic features within each gridbox were set in STICS. The main soil characteristics were obtained from the Harmonized World Soil Dataset (FAO and ISRIC, 2014; Jones and Thornton, 2015), such as physical-chemical properties (e.g. bulk density, albedo and pH) of topsoil (30 cm) and subsoil (70 cm). The predominant topographic characteristics of each gridbox, such as slope degree and elevation, were obtained from the GTOPO30 digital elevation dataset (https://lta.cr.usgs.gov/GTOPO30).

As it is not feasible to study all the existing varieties within each gridbox, a single grapevine variety was selected for the simulations. The most commonly planted variety in Portugal – Aragonez (syn. Tempranillo or Tinta-Roriz) was selected and considered for all gridboxes (IVV, 2015). The required STICS parameterizations for this variety were previously defined by Fraga et al. (2015). Viticultural management practices were also universally defined and therefore site independent. For this purpose, the default trellis system was Cordon and vine density was set to 4000 vines ha^{-1}, which are common parameters in Portuguese vineyards. In order to allow a better comparison between baseline and future yields, while maintaining wine characteristics, the simulated harvest dates were determined automatically by STICS, once berry water content reached 77% (probable alcohol concentration in the wine of 12.5%v/v) (García de Cortazar-Atauri et al., 2009).

2.3. Simulations and irrigation strategies

Previous studies indicate a general decrease in yields over Portugal under climate change scenarios, in case no adaptation measures are implemented (Fraga et al., 2016a). Given this previous knowledge, the main objective would be to minimize yield losses in the future. Therefore, to assess the role played by irrigation on viticulture under future climates, three trial runs are performed, focusing on grapevine yields: rainfed baseline period, rainfed future period and irrigated future period. The growing season precipitation (GSP; accumulated precipitation from April to September) changes between the baseline and the future period are firstly assessed, as well as its main impacts on yields. The ratio between irrigated yields and non-irrigated yields (Molden et al., 1997), was also computed for the future period (2041–2070).

Irrigation was simulated for each year, but only for the future period. Automatic irrigation is controlled by STICS based on a

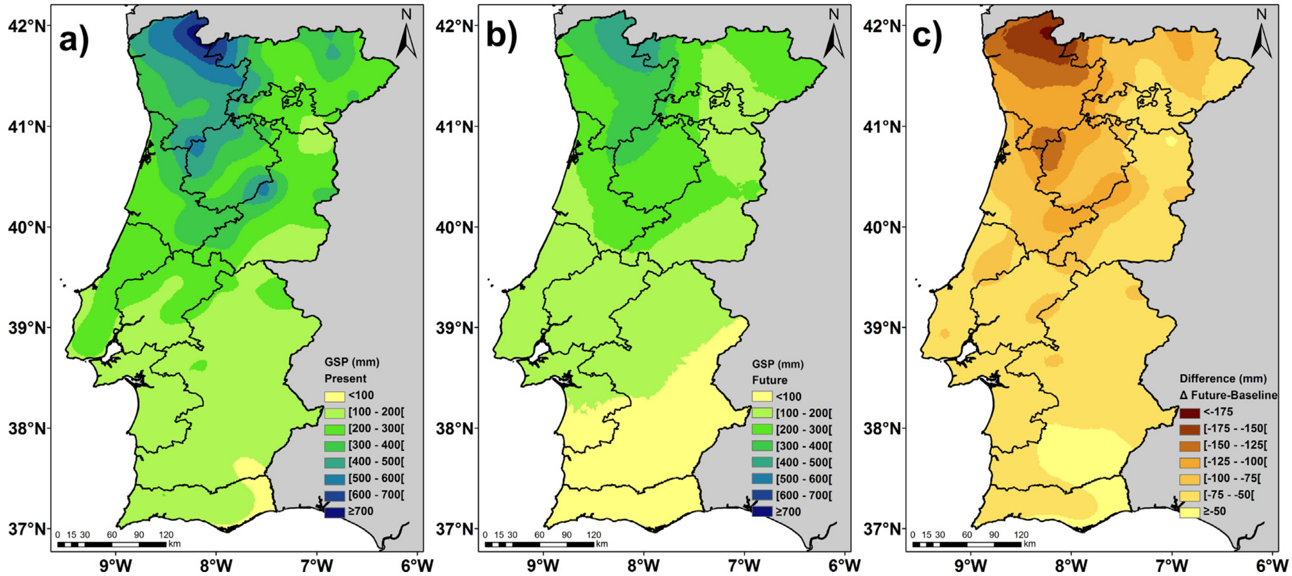

Fig. 2. a) Growing season precipitation (GSP in mm; April-September) over mainland Portugal for the baseline period (1981–2005). b) Same as (a) but for the future period (2041–2070). c) Difference between future (2041–2070) and baseline (1981–2005) GSP (mm) over mainland Portugal (Δ).

pre-defined level of the water stress index (SWFAC parameter in the model which represents stomatal stress index) (Brisson et al., 2008). To reduce non-beneficial water consumption and maximize crop water productivity, irrigation is applied only when a certain level of plant water stress is reached. For each gridbox, five stress levels were tested, ranging from high stress to low stress (SWFAC = 0.4, 0.5, 0.6, 0.7 and 0.8). Subsequently, for each gridbox, the irrigation amount that provides yields closer to the baseline was selected (lowest deviation between future and baseline yields). Thus, five irrigation maps (amounts; mm) were generated for each stress level (SWFAC = 0.4, 0.5, 0.6, 0.7 and 0.8), but only one final map was considered. STICS irrigation is applied as follows: on a daily basis, STICS assesses the plant water status and, when a certain stress threshold is reached, irrigation is automatically started with a predefined dosage. The irrigation simulates a dripping system (buried at 10 cm underground), allowing to reduce non-beneficial water consumption by ca. 90% (Brisson et al., 2008). The daily maximum amount of irrigation was set at 2 mm following previous studies (García de Cortazar-Atauri, 2006).

3. Results

3.1. Baseline and future precipitation in the growing season

Portugal presents the highest amounts of GSP in the northwestern regions (Minho and Beira-Atlântico wine regions) and the lowest amounts in the southernmost regions (Alentejo and Algarve) (Fig. 2a). As precipitation mostly occurs in the winter half of the year, a typical feature of the Mediterranean climates, GSP is substantially lower than annual precipitation totals (20–30%) (data not shown). Under RCP8.5, the 2-model ensemble mean projects a clear drying trend over all of Portugal (Fig. 2b, c), more pronounced in the more humid regions. The least affected regions by GSP decrease are the currently driest, such as inner Alentejo and Algarve. Although these projections rely only on two GCM-RCM model pairs, the climate change signal is in clear agreement with the full ensemble provided by the EURO-CORDEX project (Jacob et al., 2014).

3.2. Baseline and future yields

Grapevine yield modelled by STICS (Fig. 3a) shows higher values in the more humid coastal areas of the country and lower values in its innermost regions (Alentejo and Douro). Overall, simulated yields tend to overestimate the actual country's productivity, which is typically around 3–8 t/ha (IVV). Nonetheless, this issue has already been reported by other studies using STICS to model grapevine yields (Fraga et al., 2015; Valdes-Gomez et al., 2009). The high resolution yield map shows great detail, even allowing the differentiation of the three sub-regions inside the Douro/Porto winemaking region, i.e. the west/east yield gradient. Despite the overall agreement with empirical knowledge (excluding the positive bias), the validation of these yield maps becomes difficult, as the only countrywide dataset of observed yields comprises a much coarser spatial resolution. Additionally, these maps correspond to potential yields and do not take into account other factors, such as yield limit enforcements, pest and diseases impacts or some technical limitations not described by the model. Furthermore, in these present study, the specific soil characteristics used as model inputs represent the predominant soils inside each gridbox, which may differ from the soils at vineyard level.

Regarding future yields (Fig. 3b, c), also in accordance to Fraga et al. (2016a), projections indicate large decreases in productivity over the innermost half of the country (future yields are 60–70% with respect to baseline). In opposition, in the coastal regions, the yield reduction is much weaker (80–90% w.r.t. baseline), and there are even some yield increases in some areas (100–110% w.r.t. baseline). These outcomes are certainly tied to the projected decrease in GSP over these regions (Fig. 2c), which leads to high levels of water stress, locally reducing yields.

3.3. Irrigation as an adaptation measure

Herein, irrigation is applied as a possible adaptation measure against the decreasing yield projected for the future. Supplementary Fig. S1 (CNRM-CM5_SMHI-RCA4) and S2 (MPI-M-MPI-ESM-LR_SMHI-RCA4) show the irrigation amounts that correspond to each stress level (SWFAC = 0.4, 0.5, 0.6, 0.7 or 0.8). Results for the two climate models show very similar patterns. Fig. 4a depicts the irrigation amounts that provides the lowest deviation between future and baseline yields, determined individually for each gridbox. The irrigation patterns depict a clear north/south and west/east gradient over Portugal. Higher irrigation amounts are located in the inner south of Alentejo (>250 mm or 2500 m^3/ha), whereas lower

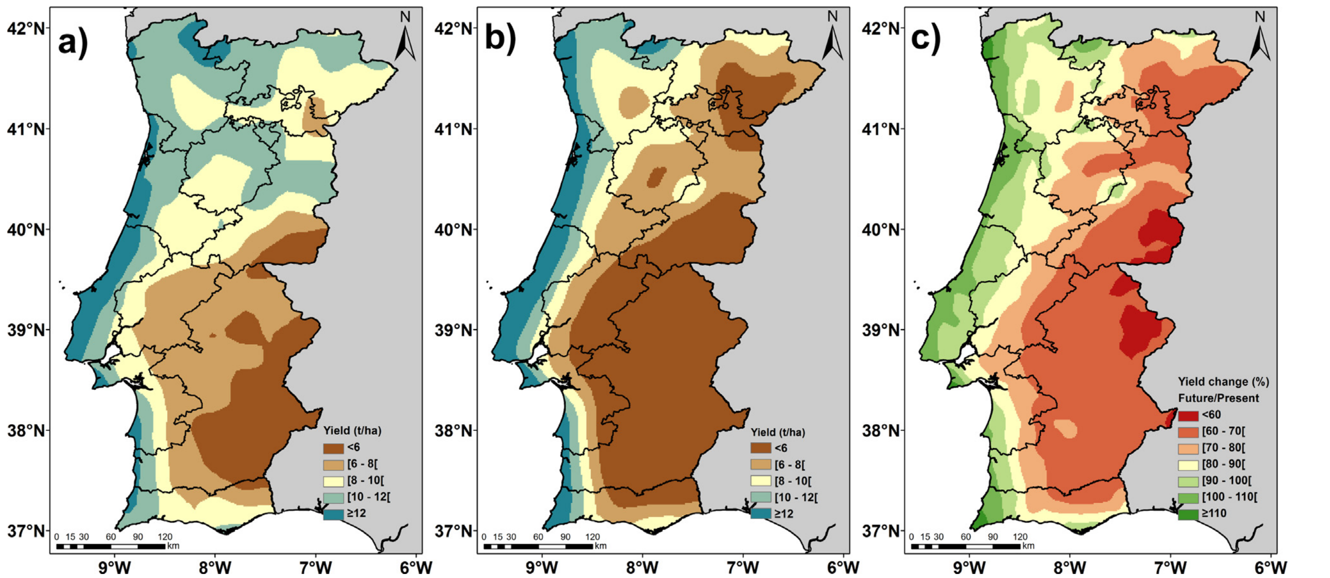

Fig. 3. a) Grapevine yield (t/ha) over mainland Portugal for the baseline period (1981–2005), calculated using the STICS crop model. b) Same as (a) but for the future period (2041–2070). c). Future (2041–2070) to baseline (1981–2005) ratio (%) for grapevine yield over mainland Portugal.

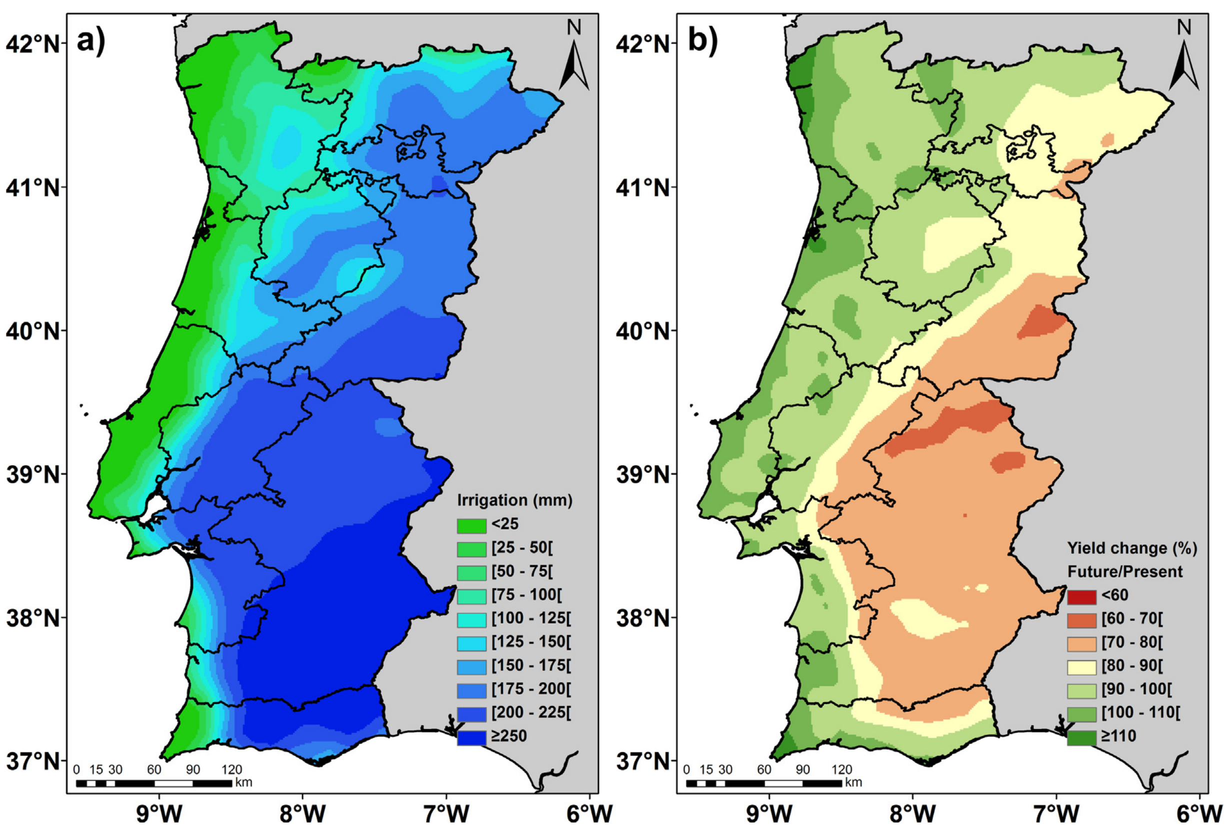

Fig. 4. a) Irrigation amounts (mm) over mainland Portugal for the future period (2041–2070) calculated using STICS. b) Future (with irrigation, 2041–2070) to baseline (without irrigation, 1981–2005) ratio (%) for grapevine yield over mainland Portugal.

irrigation values (or even no irrigation) are located in the northern coastal areas. Although some regional variability is present, irrigation closely reflects the GSP patterns over Portugal (Fig. 2a). By applying these irrigation levels, yield losses for the future can be greatly alleviated (Fig. 4b). However, the applied irrigation is not enough to completely mitigate the yield losses in inner Alentejo and Douro, where yield values still decrease, being 70–80% with respect to baseline. This may indicate that additional water per day (more than a maximum of 2 mm) or even additional measures may be required for these regions. From the spatial averages of the yield change for each winemaking region (Table 1), it is clear that Alentejo, Terras-da-Beira and Douro will be the most affected regions. These are also the regions where irrigation will show a weaker mitigation effect on future yield decreases.

Table 1
Regional/spatial averages of precipitation changes (mm), irrigation (mm), non-irrigated yield (%) and irrigated yield (%), between future and past periods and for each viticultural region in mainland Portugal.

	Precipitation change (mm)	Irrigation (mm)	Yield change% (no-irrigation)	Yield change% (irrigation)
Alentejo	−59	224	67	78
Algarve	−58	197	81	90
Beira-Atlântico	−86	102	90	100
Terras-da-Beira	−67	201	67	80
Terras-de-Cister	−95	149	80	95
Terras-do-Dão	−105	161	79	95
Douro/Porto	−71	179	74	90
Lisboa	−74	50	97	100
Minho	−132	72	91	100
Península-de-Setúbal	−66	208	77	87
Tejo	−66	204	75	85
Trás-os-Montes	−84	168	75	90

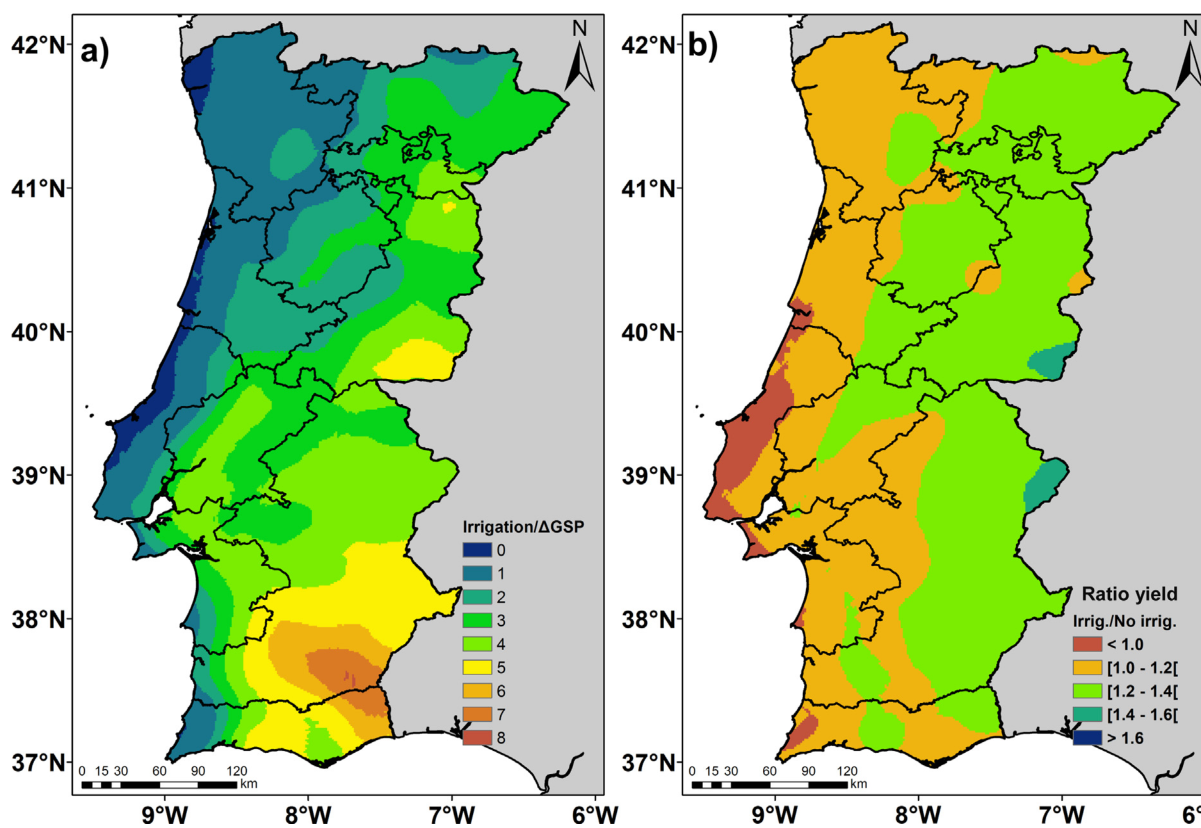

Fig. 5. a) Ratio between irrigation and the Δ of the growing season precipitation (GSP; 2041–2070 minus 1981–2005) over mainland Portugal. b) Ratio between irrigated and non-irrigated yields for the future period (2041–2070) in Portugal.

Based on these findings, a new metric was developed taking into account the required irrigation amounts and the absolute value of the GSP decrease under future climate change scenarios (future minus baseline: Δ). It is defined as the ratio between irrigation and the Δ of GSP, thus highlighting the most sensitive regions to water availability under future climates (Fig. 5a). The most sensitive regions are southern Alentejo, southern Terras-da-Beira and inner Algarve. For these regions, the required irrigation will exceed 5–8 times the reduction of precipitation. For inner Douro/Porto, upper Alentejo and Tejo, the irrigation required is around 4 times the GSP decrease. Regarding ratio between irrigated and non-irrigated yields for the future scenario (Fig. 5b), it is clear that irrigation will definitely play a more important role in the inner regions of the country. These results corroborate that the higher water input will not be enough to maintain present level yields.

4. Discussion

The present study assesses the importance of irrigation as an adaptation measure to ensure the future sustainability of viticultural yields in Portugal. The STICS crop model was used to simulate present and future grapevine yields in Portugal, pointing to a yield decrease over some of the innermost and most renowned winemaking regions of the country. Future projections also depict a decrease of the precipitation over these regions, which partially explains the yield decrease. Furthermore, the synergistic effect of severe heat and water stresses in the future, may also lead to lower yields. As an adaptation measure, grapevine irrigation was tested for the future climates. It should be noted that STICS simulates crop water stress and irrigation is only applied at a certain water stress level, mimicking a high efficiency water use strategy (deficit irrigation strategies).

The results indicate that irrigation provides a general improvement in yields over the country. Without irrigation, on average (Table 1), all regions are projected to have yield reduction in the future, from Lisboa (97%) and Minho (90%), the least affected regions, to Alentejo (67%) and Terras-da-Beira (67%), the most affected regions. It is important to note that Minho has the largest average decrease in GSP (−132 mm), but shows a relatively low decrease in yields (90%). This GSP decrease is not very important, as this region is one of the rainiest in Europe. After irrigation, the region that has the strongest yield increase is Douro/Porto, from 74% to 90% (Table 1), thus making irrigation a plausible adaptation measure for the future. Although the only regions that reach 100% of the current yield level in the future are Lisboa and Minho (Table 1), in all other regions, especially in Alentejo and inner Douro/Porto, yield levels are still projected to decrease. This decrease may be due to the synergistic effect of severe heat and water stresses (Keller, 2010). In fact, in most of the Portuguese winemaking regions, to attain future yields closer to current levels, a higher amount of water must be supplied than the projected reduction in GSP (Table 1 and Fig. 5a). This clearly indicates that future warming also has an important role in yield reduction, which can be explained by the enhanced evapotranspiration demands and the higher number of days with severe heat stress under warmer climates (van Leeuwen and Darriet, 2016).

It should be noted that STICS projections take into account the beneficial effects of higher CO_2 in the future. In fact, Fraga et al. (2016a) demonstrated that this effect partially mitigates the negative impacts of future climates on viticultural yields. However, some studies indicate that the beneficial effects of higher CO_2 concentrations may be lower than expected for perennial plants/crops (Korner et al., 2005), particularly in the long term. As such, it is possible that future yield decrease is even stronger than herein anticipated. Nonetheless, other modelling limitations should be noted. STICS is a field scale model that only simulates water flows within a given grid cell, rather than within a whole hydrological basin (the model considers runoff and deep percolation at a single point). As such, the model does not take into account the interaction between different points in space, though some runoff and deep percolation may occur, depending on the precipitation projected by the climate models. Furthermore, these local losses may or may not be reusable by downstream users, which is another aspect not taken into account by the model.

Given the projected yield levels for these regions, other adaptation measures may be needed to improve crop performance under such harsh conditions. Regions subject to water scarcity should promote higher physiological water use efficiency (Bota et al., 2016; Flexas et al., 2010). For this purpose, growers may adopt training systems with higher drought-resistant performance (e.g. *gobelet*)(van Leeuwen and Darriet, 2016) or select more drought resilient varieties and/or rootstocks (Bota et al., 2016; Duchene et al., 2010; Harbertson and Keller, 2012; Keller et al., 2011). Plant density and total vine leaf area are also important aspects under drought conditions. Other aspects that can improve crop water productivity comprise adjustments to traditional tillage systems and soil management practices or considering specific cover crops (Bahar and Yasasin, 2010; Kvaternjak et al., 2008). The combination of all these techniques may actually improve crop water productivity and provide a compromise solution between environment, plant water requirements and economic costs for growers (Chaves et al., 2007; Chaves et al., 2010; dos Santos et al., 2003; Ferreira et al., 2012).

The implications of applying irrigation as a climate change adaptation strategy should also take into account its impacts on grapes and wine composition (Jones et al., 2005). When targeting high quality winemaking (in Portugal and in many other wine regions in the world), many growers are adverse to the application of irrigation, aiming to preserve wine types. As such, the cost-effectiveness of irrigation must also be taken into account under future climates. Although the present study simulations aim at achieving the same yields and alcohol level, both in the baseline and future scenarios, applying irrigation may undoubtedly modify the wine characteristics of each region (van Leeuwen and Darriet, 2016; Webb et al., 2008). The amounts of irrigation simulated for the innermost areas of the country may certainly modify water stress levels, which in turn may affect the overall wine composition (Storchi et al., 2005; Tonietto, 1999). However, given the amounting evidence for a change in grape composition under future warmer and dryer climates (Jones et al., 2005), if irrigation (scheduling and amounts) and water stress levels are carefully monitored and controlled, this practice may indeed be beneficial in some cases (Costa et al., 2016; van Leeuwen and Darriet, 2016).

One challenge to the proposed adaptation measure will be providing sufficient water during the necessary irrigation periods, which coincide with the driest periods of the year. In Portugal, traditional irrigation systems (e.g. manual irrigation) are still usually applied, but often have high non-beneficial water consumption (high soil runoff and evaporation). Technological advances in irrigation science, such as the adoption of deficit irrigation strategies (as the drip system simulated in the current study), will thereby be critical in the next decades. However, to meet irrigation demands, the creation (or maintenance) of large water reservoirs is indeed one of the key aspects (Batista et al., 2001). In Portugal, over the last decade, a significant effort has been devoted to create a large artificial reservoir in the Alentejo region (Alqueva dam) for irrigation purposes, which can also be used by regional viticulture. Nevertheless, decision-makers must ensure that these new approaches do not aggravate the adverse effects of increasing agricultural water usage, including the sustainability of the water resources (EEA, 2009) and the commitment to the EU water framework directive (http://ec.europa.eu/environment/water/water-framework/index_en.html). Balanced decisions, based on research and on innovation technologies and solutions, should be envisioned in order to maintain the sustainability of both the winemaking sector and the environment.

5. Conclusions

Future projections for viticultural yield in Portugal show decreases throughout the country, particularly in the innermost winemaking regions. The present study analyzed irrigation as a possible adaptation measure, which may significantly alleviate some detrimental climate change impacts, thus reducing the projected yield decreases. Nonetheless, in some warmer and dryer regions, such as inner Alentejo and Douro/Porto, yield levels are still projected to decrease, even with suitable irrigation. Hence, given these projections, additional adaptation measures should also be envisioned for the future sustainability of the national winemaking sector.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agwat.2017.10.023.

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